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Fused Silica Micro-structured Fibers for Delivery of Short Pulsed High Peak Power Laser Light

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Abstract: A range of micro-structured optical fibers have been developed in recent years, including Negative Curvature Fiber, which is particularly suited to delivery of high average and high peak power pulses, as described in this presentation.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2270) Fiber characterization; (060.5295) Photonic crystal fibers; (350.3390) Laser materials processing.

1. Background

One of the most significant advances in optical fiber technology in the recent past has been the realization of microstructured silica fibers that guide light in air. Hollow Core Photonic Bandgap Fibers (HC-PBGFs) were first demonstrated over a decade ago. These fibers were able to transmit powers and pulse lengths that could not be delivered through standard optical fibers. Since then, some of the limitations of such fibers have been established: consistent fabrication is difficult, their attenuation increases as one moves to longer and to shorter wavelengths, and at shorter wavelengths the fabrication of high-quality structures becomes increasingly difficult as surface tension forces become stronger.

The past two years have seen dramatic progress in a competing and simpler design for hollow-core fiber based on the concept of antiresonant core walls, that guide via the Anti-Resonant Reflecting Optical Waveguiding (ARROW) mechanism. When compared to HC-PBGFs, these antiresonant fibers (ARFs) are much simpler to fabricate, and have been demonstrated to have a greatly reduced overlap between the light travelling within the fiber and the silica forming the cladding – roughly 100× better than the earlier designs. They thus provide a higher damage threshold for optical beam delivery. Moreover the corresponding reduction in the scattering loss of this fiber type allows them to be used for efficient transmission in the visible and ultraviolet wavelength regime. Indeed, it is quite possible that these designs could be used to produce the lowest optical loss ever in an optical fiber. These very recent developments offer the best opportunities yet for high-beam-quality delivery of high-power pulsed light. In this presentation I will describe the most recent results obtained in the application of these fibers to the delivery of short pulsed, high peak power laser light.

2. Anti-resonant fibers (ARFs)

A typical ARF is compared with an HC-PBGF in figure 1. Both fibers are fabricated using the same process, namely a stack and draw technique [1] where circular capillaries are used to fabricate a preform with a jacketing tube, which is subsequently drawn down to produce the final fiber dimensions – see figure 2. A typical HC-PBGF requires ~250 capillaries to be stacked, whereas the ARF uses only 8 capillaries, greatly simplifying the manufacturing process and increasing manufacturing yield. The critical fiber parameters such as the core wall thickness, core diameter and radius of the negative curvature of the core wall are controlled by applying different pressures to the core and the cladding during the fiber drawing process [1]. Fused silica ARFs have been fabricated for operation at a wide range of wavelengths, from visible (green) [2] through to the mid IR (3.5 μm wavelength) [3].

The ARF guidance mechanism is described as an Anti-Resonant Reflecting Optical Waveguiding (ARROW) phenomenon where the core wall structure acts as a Fabry-Perot resonant cavity [4]. The wavelengths that are not in resonance with the core wall are reflected back into the core and propagate with low loss as a result of destructive interference in the Fabry-Perot resonator. The frequencies resonant with the wall cannot be confined and therefore leak away to the cladding region where they are highly attenuated. Consequently the thickness of the core wall (or capillaries) determines the wavelength range for guidance. One unfortunate feature of this ARF geometry is the contact points (or cladding nodes) between adjacent capillaries (see Figure 1(b)) that can act as independent, but highly lossy, waveguides. However, the negative curvature of the core wall acts to physically distance the guided core mode from these potential lossy modes and therefore coupling to them is significantly reduced [4].

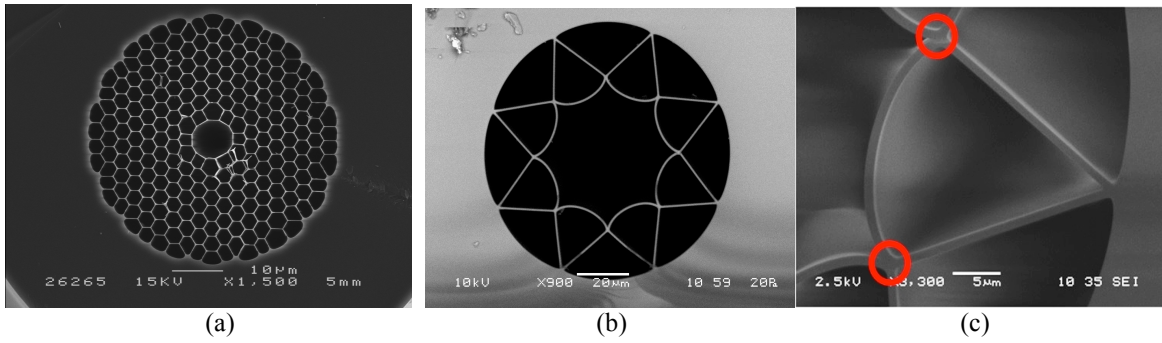


Figure 1. (a) HC-PBGF, fabricated from ~250 capillaries plus jacket; (b) ARF, fabricated from 8 capillaries plus jacket; (c) close-up of ARF showing the capillary forming the negative curvature of the fiber core wall and the cladding nodes (red circles). Both fibres are designed for operation in the 1 μm wavelength region.

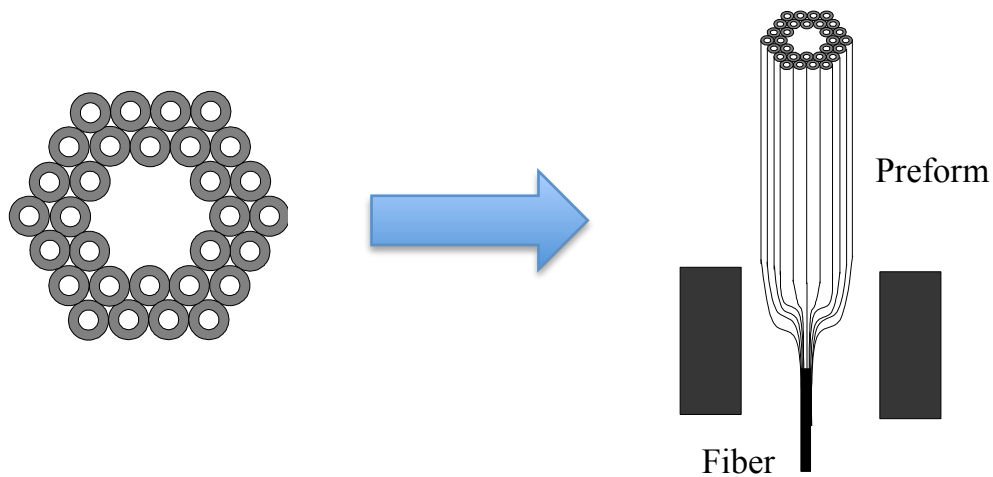


Figure 2: Stacking of silica capillaries (left) to form a large scale preform for a microstructured fiber. The large scale preform is drawn down in a fiber furnace to produce the micro-structured hollow core fiber (right).

A similar (but slightly more complex) variation of the ARF design is the hypocycloid fiber reported by Heckl et al [5], which typically uses ~50 capillaries; however here a different guidance mechanism is proposed. This fiber has also demonstrated delivery of high pulse energies.

The attenuation spectrum of a typical ARF, designed for operation in the 1 μm wavelength region is shown in figure 3. The absorption is reasonably low (and can be reduced by further optimization) and hence suitable for localized delivery of high peak power laser light for applications in manufacturing, surgery, or laser ignition.

3. Damage Limitations – delivery of ns pulsed light

For the ns regime at 1064 nm a Spectra Physics Q-switched laser ($M^2 < 1.3$) was used. This provided 60 ns pulses with a pulse energy > 1 mJ and an average power of 18.2 W at a repetition rate of 15 kHz. Pulse delivery tests were conducted with both a 0.7 m straight fiber and a 10.5 m fiber coiled to a diameter of 60 cm. Both fibers proved capable of handling the maximum pulse energy from the laser without damage, with the 0.7 m straight fiber delivering pulses of 1.1 mJ at an average power of 16.3 W and a peak power of 18.3 kW [6]. Due to the fiber loss the delivered pulse for the 10.5 m coiled fiber falls to 0.8 mJ. The damage threshold could not be reached with the 60 ns system however using a shorter pulsed laser system (9 ns at 1064 nm) the fiber failed at 3.2 mJ. Assuming the commonly accepted scaling of damage threshold with pulse duration of $t^{0.5}$ [6] this translates to an 8 mJ pulse at 60 ns which is 16 times greater than reported with the HC-PBGF design [7].

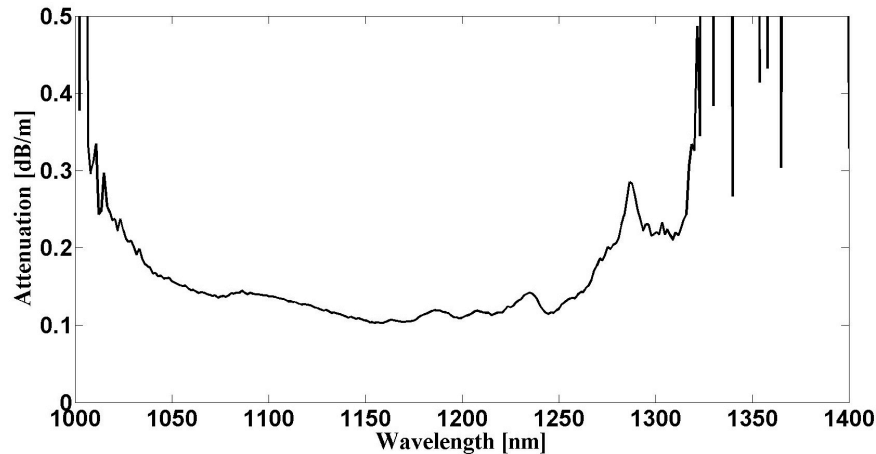


Figure 3. Attenuation spectrum of a typical NCF designed for the 1 μm wavelength regime.

Picosecond delivery was tested using a Trumpf picosecond laser, which provided 6 ps pulses at a 400 kHz repetition rate, with pulse energies of up to 116 μJ at 1030 nm and average and peak powers of 46.3 W and 19.3 MW respectively [6]. 92 μJ pulses (average power of 36.7 W and peak power of 15.3 MW) were delivered through a 1 m straight length of fiber. Delivery was also carried out using an 8 m length ARF coiled to a diameter of 23 cm. In this instance, due to additional bend loss, the transmitted energy was 49 μJ (average power of 19.6 W and peak power of 5.6 MW). The delivered pulse length was measured using intensity autocorrelation, demonstrating that there is no measurable dispersion of a 6 ps pulse delivered through the 1 m straight fiber. However, the pulse did exhibit broadening (from 6 ps to 8.7 ps) after propagation through the longer (8 m) coiled fiber [6]. There was no noticeable distortion of the pulse shape and no degradation of the optical spectra of pulse delivered pulse by the ARF compared with the laser output [6].

4. Discussion and conclusions

Microstructured fused silica fibers have had a significant impact in applications where flexible delivery of short pulse, high peak power light is required. The recently-developed class of microstructured fibers that guide via the ARROW mechanism is particularly important, since these are much easier to manufacture, and can provide robust single-mode guidance at shorter wavelengths than the earlier fibers based on the photonic bandgap guidance mechanism (hollow core photonic bandgap fiber, HC-PBGF). These fibers have proven capable of delivering pulse energies to a level suitable for ignition applications, i.e. a few mJ in the ns regime.

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